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I hereby certify that the accompanying Utility Patent Application (12 sheets of formal drawings (FIGURES 1-12) and 48 pages of specification, including 17 pages of claims (claims 1 – 96) and 1 page of abstract), Utility Patent Application Transmittal (PTO/SB/05, 1 page), Declaration (PTO/SB/01, 2 pages), Application Data Sheet (3 pages), a return receipt postcard and this Transmittal Letter are being deposited with proper postage with the United States Postal Service “Express Mail Post Office to Addressee” service under 37 C.F.R. 1.10 on the date indicated above and addressed to: Mail Stop Patent Application, Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.



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MULTI-WAVELENGTH OPTICAL FIBER

Cross-Reference to Related Applications

[0001] This application is a continuation of International Application No. PCT/US02/20817, which has an international filing date of July 1, 2002, and is entitled "Multi-Wavelength Optical Fiber", and which in turn claims priority to United States Provisional Patent Application Serial No. 60/302,603, which was filed July 2, 2001 and is also entitled "Multi-Wavelength Optical Fiber". The foregoing applications are incorporated herein by reference.

Technical Field

[0002] This invention relates to optical fibers (e.g., fiber lasers and fiber amplifiers), and systems containing such optical fibers.

Background

[0003] Certain optical fibers can be used as fiber amplifiers or fiber lasers.

[0004] Fiber amplifiers are typically used to amplify an input signal. Often, the input signal and a pump signal are combined and passed through the fiber amplifier to amplify the signal at the input wavelength. The amplified signal at the input wavelength can then be isolated from the signal at undesired wavelengths.

[0005] Raman fiber lasers can be used, for example, as energy sources. In

general, Raman fiber lasers include a pump source coupled to a fiber, such as an optical fiber, having a gain medium with a Raman active material. Energy emitted from the pump source at a certain wavelength λ_p , commonly referred to as the pump energy, is coupled into the fiber. As the pump energy interacts with the Raman active material in the gain medium of the fiber, one or more Raman Stokes transitions can occur within the fiber, resulting in the formation of energy within the fiber at wavelengths corresponding to the Raman Stokes shifts that occur (e.g., λ_{s1} , λ_{s2} , λ_{s3} , λ_{s4} , etc.).

[0006] Generally, the Raman active material in the gain medium of a Raman fiber laser may have a broad Raman gain spectrum. Usually, conversion efficiency varies for different frequencies within the Raman gain spectrum and many Raman active materials exhibit a peak in their gain spectrum, corresponding to the frequency with highest conversion efficiency. Additionally, the gain spectrum for different Raman active materials may be substantially different, partially overlapping, or of different conversion efficiency.

[0007] Typically, a Raman fiber laser is designed so that the energy formed at one or more Raman Stokes shifts is substantially confined within the fiber. This can enhance the formation of energy within the fiber at one or more higher order Raman Stokes shifts. Often, the fiber is also designed so that at least a portion of the energy at wavelengths corresponding to predetermined, higher order Raman Stokes shifts (e.g., λ_{sx}) where x is equal to or greater than one) is allowed to exit the fiber.

Summary

[0008] In general, the invention relates to optical fibers (e.g., fiber lasers and fiber amplifiers), and systems containing such optical fibers.

[0009] In one aspect, the invention features a fiber that includes an optical fiber containing a gain medium having a Raman active material with a Raman gain spectrum. The optical fiber is configured to receive energy at a wavelength λ_p . The fiber also includes at least three pairs of reflectors disposed in the optical fiber. Each pair of

reflectors forms a resonance cavity with a resonance frequency. Each resonance cavity has an index, and the index of each resonance cavity is different than the index of the other resonance cavities. For a resonance cavity having an index with a value M (M is an integer having a value of at least one), the resonance cavity has a resonance frequency (c/λ_{sm}), where $\lambda_{sm}^{-1} = \lambda_p^{-1} - \sum_M \lambda_{rm}^{-1}$, where (c/λ_{rm}) is a frequency within the Raman gain spectrum of the Raman active material contained in the gain medium, and c is the speed of light. For a resonance cavity having an index with a value N, the resonance cavity has a resonance frequency (c/λ_{sn}). The resonance cavity having the index value N overlaps only with a resonance cavity having a resonance frequency ($c/\lambda_{s(n-1)}$) and with a resonance cavity having a resonance frequency ($c/\lambda_{s(n+1)}$) (N is an integer having a value of at least two). In the case where N corresponds to the highest index number (i.e., the cavity with the lowest resonance frequency), the cavity overlaps only with a resonance cavity having a resonance frequency ($c/\lambda_{s(n-1)}$).

[0010] For example, $\lambda_{s1}^{-1} = \lambda_p^{-1} - \lambda_{r1}^{-1}$, where λ_{r1}^{-1} is a frequency in the Raman gain spectrum of the active material. As another example, $\lambda_{s2}^{-1} = \lambda_p^{-1} - \lambda_{r1}^{-1} - \lambda_{r2}^{-1}$, where λ_{r2}^{-1} is a frequency in the Raman gain spectrum of the active material. As a further example, $\lambda_{s3}^{-1} = \lambda_p^{-1} - \lambda_{r1}^{-1} - \lambda_{r2}^{-1} - \lambda_{r3}^{-1}$, where λ_{r3}^{-1} is a frequency in the Raman gain spectrum of the active material. λ_{r1} , λ_{r2} and/or λ_{r3} can be the same or different.

[0011] The optical fiber can include, for example, three, four, five, six, seven, eight, nine, 10 or more than 10 pairs of reflectors.

[0012] In some embodiments, at least one pair of reflectors has a first reflector and a second reflector. The first reflector is disposed in the optical fiber closer to a point where energy at the wavelength λ_p enters the optical fiber than the second reflector, and the second reflector is configured to reflect only a portion of energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors. The first reflector can be configured to reflect substantially all energy impinging thereon at the resonance frequency for the resonance cavity formed by the at

least one pair of reflectors. The second reflector can be configured to reflect less than about 98% (e.g., less than about 95%, less than about 90%, less than about 75%, less than about 60%, less than about 50%, less than about 25%, less than about 10%) of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors. The amount of energy at the resonance frequency for the resonance cavity that the second reflector is capable of reflecting can be variable.

[0013] In certain embodiments, each pair of reflectors has a first reflector and a second reflector, and for each pair of reflectors: the first reflector is disposed in the optical fiber closer to a point where energy at the wavelength λ_p enters the optical fiber than the second reflector and the second reflector is configured to reflect only a portion of energy impinging thereon at the resonance frequency for the resonance cavity formed by the first and second reflectors.

[0014] At least one resonance cavity in the optical fiber can have a suppressor disposed therein. The suppressor can be configured to substantially suppress formation of energy at a frequency (c/λ_x) where $\lambda_x^{-1} = \lambda_z^{-1} - \lambda_a^{-1}$, and (c/λ_z) is the resonance frequency of the resonance cavity and (c/λ_a) is a frequency in the Raman gain spectrum of the active material in the gain medium of the fiber. The suppressor can be, for example, formed of one or more long period gratings.

[0015] One pair of reflectors can have first and second reflectors, and the first and second reflectors can be configured to reflect substantially all energy impinging thereon at the resonance frequency of the corresponding resonance cavity.

[0016] In some embodiments, the at least three pairs of reflectors includes a first pair of reflectors and a second pair of reflectors. The first pair of reflectors has first and second reflectors, and the second pair of reflectors has first and second reflectors. The first and second reflectors of the first pair of reflectors are configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by first pair of reflectors, and the first and second reflectors of the second

pair of reflectors are configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by the second pair of reflectors.

[0017] In certain embodiments, the at least three pairs of reflectors includes a first pair of reflectors, a second pair of reflectors and a third pair of reflectors. The first pair of reflectors has first and second reflectors, the second pair of reflectors has first and second reflectors, and the third pair of reflectors has first and second reflectors. The first and second reflectors of the first pair of reflectors are configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by the first pair of reflectors, the first and second reflectors of the second pair of reflectors are configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by the second pair of reflectors, and the first and second reflectors of the third pair of reflectors are configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by the third pair of reflectors.

[0018] The fiber can further include an additional reflector disposed in the optical fiber. The additional reflector can be configured to at least partially reflect energy impinging thereon (e.g., reflect substantially all energy impinging thereon) at the wavelength λ_p .

[0019] One or more of the pairs of reflectors can be formed of a pair of fiber Bragg gratings.

[0020] The Raman active material(s) can be, for example, GeO₂, P₂O₅, SiO₂, B₂O₃ or SiO_xF_y.

[0021] In another aspect, the fiber can be used in a fiber laser system that also includes an energy source configured to emit energy at a wavelength λ_p .

[0022] In a further aspect, the invention features a fiber that includes an optical

fiber containing a gain medium having a Raman active material. The optical fiber is configured to receive energy at a wavelength λ_p . The fiber also includes at least three pairs of reflectors disposed in the optical fiber. Each pair of reflectors forms a corresponding resonance cavity with a corresponding resonance frequency. The resonance frequency of each resonance cavity is different than the resonance frequency of any other cavity. The optical fiber is substantially devoid of a portion containing more than two of the resonance cavities. The fiber can be incorporated in a system containing an energy source capable of emitting energy at the wavelength λ_p .

[0023] In one aspect, the invention features a fiber that includes an optical fiber containing a plurality of sections including a first section having a gain medium including a first Raman active material and a second section having a gain medium including a second Raman active material. The second Raman active material can be the same as or different than the first Raman active material. Alternatively, the concentration of the Raman active material in the second section can be the same as or different than the concentration of the Raman active material in the first section of fiber. Or, the diameter of the fiber core of the second section of fiber can be the same as or different than the diameter of the fiber core of the first section of fiber. The optical fiber is configured to receive energy at a wavelength λ_p . At least three pairs of reflectors are disposed in the optical fiber. Each pair of reflectors forms a corresponding resonance cavity with a corresponding resonance frequency. The optical fiber is substantially devoid of a portion containing more than two of the resonance cavities. The fiber can be incorporated in a system that includes an energy source configured to emit energy at a wavelength λ_p .

[0024] In another aspect, the invention features a fiber that includes an optical fiber having a gain medium having a Raman active material. The optical fiber is configured to receive energy at a wavelength λ_p . The fiber also includes a plurality of reflectors disposed in the optical fiber. At least some of the plurality of reflectors form resonance cavities in the optical fiber. Each resonance cavity has a resonance frequency. The resonance frequency of each resonance cavity can be different than the resonance frequency of any other cavity. The plurality of reflectors are configured so that when the

optical fiber receives energy at the wavelength λ_p , the ratio of the output power at a desired wavelength to the pump power can be at least 20% (e.g., at least 30%, at least 40%, at least 50%, at least 60%, at least 70%, at least 80%, at least 90%, at least 95%, at least 98%) of the theoretical limit.

[0025] In a further aspect, the invention features a fiber that includes an optical fiber having a gain medium having a Raman active material. The optical fiber is configured to receive energy at a wavelength λ_p . The fiber also includes a plurality of reflectors disposed in the optical fiber. At least some of the plurality of reflectors form resonance cavities in the optical fiber. Each resonance cavity has a resonance frequency. The resonance frequency of each resonance cavity can be different than the resonance frequency of any other cavity. The plurality of reflectors are configured so that when the optical fiber receives energy at the wavelength λ_p , the ratio of the total output power at one or more desired wavelengths to the pump power can be at least 20% (e.g., at least 30%, at least 40%, at least 50%, at least 60%, at least 70%, at least 80%, at least 90%, at least 95%, at least 98%) of the theoretical limit.

[0026] In one aspect, the invention features a system that includes a fiber having the structure described herein. The system also includes a splitter configured so that output energy from the fiber can be coupled into the splitter. The system further includes a plurality of optical fibers (e.g., at least five fibers, at least 25 fibers, at least 50 fibers, at least 75 fibers, at least 100 fibers, at least 250 fibers, at least 500 fibers) configured so that energy output from the splitter can be coupled into one or more of the plurality of fibers.

[0027] In another aspect, the invention features a system that includes a pump laser and a fiber laser coupled to the pump laser so that energy output by the pump laser can be coupled into the fiber laser. The system also includes a fiber as described herein. The fiber is coupled to the fiber laser so that energy output by the fiber laser can be coupled into the fiber. The system can further include an output cascade coupled to the fiber so that energy output by the fiber can be coupled into the output cascade.

[0028] In one aspect, the invention features a fiber that includes an optical fiber containing a gain medium having a Raman active material with a Raman gain spectrum. The optical fiber is configured to receive energy at a wavelength λ_p . The fiber also includes at least three pairs of reflectors disposed in the optical fiber. Each pair of reflectors forms a resonance cavity with a resonance frequency. Each resonance cavity has an index, and the index of each resonance cavity is different than the index of the other resonance cavities. For a resonance cavity having an index with a value M (M is an integer having a value of at least one), the resonance cavity has a resonance frequency (c/λ_{sm}) , where $\lambda_{sm}^{-1} = \lambda_p^{-1} - \sum_M \lambda_{rm}^{-1}$, where (c/λ_{rm}) is a frequency within the Raman gain spectrum of the Raman active material contained in the gain medium, and c is the speed of light. For a resonance cavity having an index with a value N, the resonance cavity has a resonance frequency (c/λ_{sn}) , and the reflectors are configured so that at least two resonance cavities do not overlap. In another aspect, the invention features a system including an energy source coupled to such a fiber.

[0029] In some embodiments, the invention can provide a Raman fiber laser having a relatively high output power at one or more desired wavelengths relative to the power of the pump laser that is received by the fiber (e.g., at the wavelength λ_p). For example, the ratio of the output power at one or more desired wavelengths to the pump power can be at least 20% (e.g., at least 30%, at least 40%, at least 50%, at least 60%, at least 70%, at least 80%, at least 90%, at least 95%, at least 98%) of the theoretical limit.

[0030] As used herein, the theoretical limit of the ratio of the output power at a desired wavelength λ_x to the pump power (λ_p) is the ratio of the wavelength of λ_p to the wavelength of λ_x , when optical losses are neglected.

[0031] As used herein, the theoretical limit of the ratio of the total output power at one or more desired wavelengths (e.g., $\lambda_x, \lambda_y, \lambda_z$) to the pump power λ_p is the sum of the individual ratios the wavelength of λ_p to the desired wavelength(s) (e.g., $\lambda_p/\lambda_x, \lambda_p/\lambda_y,$

λ_p/λ_z , respectively).

[0032] In some embodiments, the input power can be at least about 0.1 Watt (e.g., at least about 0.5 Watt, at least about one Watt, at least about 2 Watts, at least about 5 Watts, at least about 10 Watts).

[0033] In certain embodiments, the output power at a desired wavelength can be at least about 0.1 Watt (e.g., at least about 0.5 Watt, at least about one Watt, at least about 2 Watts, at least about 5 Watts, at least about 10 Watts).

[0034] In certain embodiments, the total output power at one or more desired wavelengths can be at least about 0.1 Watt (e.g., at least about 0.5 Watt, at least about one Watt, at least about 2 Watts, at least about 5 Watts, at least about 10 Watts).

[0035] In some embodiments, the output power at one or more undesired wavelengths can be relatively low (e.g., less than about one Watt, less than about 0.5 Watt, less than about 0.1 Watt, less than about 0.05 Watt).

[0036] In certain embodiments, it is a feature of the invention that λ_p pumps only λ_{s1} .

[0037] In some embodiments, it is a feature of the invention that energy at a given Stokes shift frequency is pumped only by one other Stokes shift frequency.

[0038] In certain embodiments, the fibers can be used as amplifiers rather than lasers.

[0039] Features, objects and advantages of the invention are in the description, drawings and claims.

Description of Drawings

- [0040] Fig. 1 is a schematic representation of an embodiment of a Raman fiber laser system;
- [0041] Fig. 2 is a plot of output energy intensity as a function of pump energy intensity for embodiments of a Raman fiber laser;
- [0042] Fig. 3 is a schematic representation of an embodiment of a Raman fiber laser system;
- [0043] Fig. 4 is a schematic representation of an embodiment of a Raman fiber laser system;
- [0044] Fig. 5 is a schematic representation of an embodiment of a Raman fiber laser system;
- [0045] Fig. 6 is a schematic representation of an embodiment of a Raman fiber laser system;
- [0046] Fig. 7 is a schematic representation of an embodiment of a Raman fiber laser system;
- [0047] Fig. 8 is a schematic representation of an embodiment of a fiber amplifier system;
- [0048] Fig. 9 is a schematic representation of an embodiment of a fiber amplifier system;
- [0049] Fig. 10 is a schematic representation of an embodiment of a fiber laser system;

[0050] Fig. 11 is a schematic representation of an embodiment of a fiber amplifier system; and

[0051] Fig. 12 is a schematic representation of an embodiment of a Raman fiber laser system.

[0052] Like reference symbols in the various drawings indicate like elements.

Detailed Description

[0053] Fig. 1 shows an embodiment of a Raman fiber laser system **1000** including a laser **100** and an optical fiber **110**. Laser **100** is configured so that energy emitted by laser **100** at a wavelength λ_p is coupled into optical fiber **110**. Optical fiber **110** has a gain medium containing a Raman active material. Examples of Raman active materials include GeO_2 , P_2O_5 , SiO_2 , B_2O_3 , SiO_xF_y , and the like.

[0054] Optical fiber **110** includes a first pair of reflectors **120** and **130** (e.g., a pair of fiber Bragg gratings). Reflector **120** is configured to reflect substantially all (e.g., about 100 %) energy impinging thereon at a wavelength λ_{s1} , where $\lambda_{s1}^{-1} = \lambda_p^{-1} - \lambda_{r1}^{-1}$, where (c/λ_{r1}) is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in the gain medium of fiber **110**, and c is the speed of light. Reflector **130** is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength λ_{s1} . Reflectors **120** and **130** form a resonance cavity **140** in fiber **110** for energy at wavelength λ_{s1} .

[0055] Optical fiber **110** also includes a reflector **125** that is configured to reflect substantially all (e.g., about 100%) energy impinging thereon at wavelength λ_p .

[0056] Optical fiber **110** further includes a second pair of reflectors **150** and **160** (e.g., a pair of fiber Bragg gratings). Reflector **150** is configured to reflect substantially

all (e.g., about 100%) energy impinging thereon at a wavelength λ_{s2} , where $\lambda_{s2}^{-1} = \lambda_{s1}^{-1} - \lambda_{r2}^{-1}$, where (c/λ_{r2}) is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in the gain medium of fiber **110** (λ_{r2}^{-1} may be the same as or different from λ_{r1}^{-1}). Reflector **160** is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength λ_{s2} . Reflectors **150** and **160** form a resonance cavity **170** in fiber **110** for energy at wavelength λ_{s2} . In certain embodiments, reflector **125** is relatively close to reflector **150**. In some embodiments, reflector **150** can be in cavity **170**.

[0057] With this arrangement, as energy at λ_p enters optical fiber **110**, the energy at λ_p propagates through fiber **110** and impinges upon reflector **125** where it is reflected and propagates in fiber **110** in the reverse direction. As energy at λ_p propagates through fiber **110**, it interacts with the Raman active material in the gain medium of fiber **110** to create energy at wavelength λ_{s1} . Energy at λ_{s1} in cavity **140** that is propagating in the forward direction impinges upon reflector **130**. A portion of the energy at λ_{s1} that impinges on reflector **130** is reflected backward, and a portion of the energy at λ_{s1} that impinges on reflector **130** continues to propagate through fiber **110** in the forward direction and exits fiber **110** (e.g., at an end **115** of fiber **110**). The portion of energy at λ_{s1} that is reflected by reflector **130** propagates through fiber **110** in the reverse direction until it reaches reflector **120** where it is reflected and then propagates through fiber **110** in the forward direction. Some of the energy at wavelength λ_{s1} continues to propagate in fiber **110** in the forward and in reverse directions in resonance cavity **140**, and some of the energy at wavelength λ_{s1} exits resonance cavity **140** through reflector **130** and ultimately exits fiber **110** (e.g., at end **115**).

[0058] As energy at wavelength λ_{s1} propagates through fiber **110**, it interacts with the Raman active material in the gain medium of fiber **110** to create energy at wavelength λ_{s2} . Energy at wavelength λ_{s2} in cavity **170** that is propagating in the reverse direction is

reflected by reflector 150 and then propagates through fiber 110 in the forward direction. Energy at wavelength λ_{s2} propagating in cavity 170 in the forward direction impinges on reflector 160. Some of the energy at λ_{s2} impinging on reflector 160 is reflected by reflector 160 and then propagates through cavity 170 in the reverse direction, and some of the energy at λ_{s2} impinging on reflector 160 passes through reflector 160 and exits fiber 110 (e.g., at end 115). It is to be noted that, in this embodiment, λ_p does not directly pump λ_{s2} .

[0059] Resonance cavities 110 and 140 are linked resonance cavities because, while a portion of these cavities overlaps, a portion of the cavities does not overlap.

[0060] Without wishing to be bound by theory, it is believed that this design can allow for enhanced control of the intensity of energy output by fiber 110 at wavelengths λ_{s1} and λ_{s2} by controlling (e.g., independently controlling) the transmission of reflectors 130 and/or 160, and/or the intensity of the pump energy. For the case where reflector 130 is positioned close to reflector 160 (i.e., $z_{125} \approx z_{150}$ and $z_{130} \approx z_{160}$, where z_x is to the position of reflector x), it is believed that the performance of fiber 110 can be explained, at least in part, using the following system of equations.

$$\left. \begin{aligned} \frac{dI_p^+}{dz} &= -g_p(I_{\lambda_{s1}}^+ + I_{\lambda_{s1}}^-) \times I_p^+ - \alpha_p I_p^+ = -\frac{dI_p^-}{dz} \\ \frac{dI_{\lambda_{s1}}^+}{dz} &= g_1 I_{\lambda_{s1}}^+ \times (I_p^+ + I_p^-) - \alpha_1 I_{\lambda_{s1}}^+ = -\frac{dI_{\lambda_{s1}}^-}{dz} \end{aligned} \right\} \text{..... along cavity 140}$$

$$\left. \begin{aligned} \frac{dI_{\lambda_{s1}}^+}{dz} &= -\tilde{g}_1 I_{\lambda_{s1}}^+ \times (I_{\lambda_{s2}}^+ + I_{\lambda_{s2}}^-) - \alpha_1 I_{\lambda_{s1}}^+ = -\frac{dI_{\lambda_{s1}}^-}{dz} \\ \frac{dI_{\lambda_{s2}}^+}{dz} &= g_2 I_{\lambda_{s2}}^+ \times (I_{\lambda_{s1}}^+ + I_{\lambda_{s1}}^-) - \alpha_2 I_{\lambda_{s2}}^+ = -\frac{dI_{\lambda_{s2}}^-}{dz} \end{aligned} \right\} \text{..... along cavity 170}$$

with the boundary conditions:

$$\begin{aligned}
I_p^+(z=0) &= I_0; \\
I_p^-(z=z_{125}) &= R_p \times I_p^+(z=z_{125}); \\
I_{\lambda_{s1}}^+(z=z_{120}) &= R_{\lambda_{s1}}^{120} \times I_{\lambda_{s1}}^-(z=z_{120}), I_{\lambda_{s1}}^-(z=z_{130}) = R_{\lambda_{s1}}^{130} \times I_{\lambda_{s1}}^+(z=z_{130}); \\
I_{\lambda_{s2}}^+(z=z_{150}) &= R_{\lambda_{s2}}^{150} \times I_{\lambda_{s2}}^-(z=z_{150}), I_{\lambda_{s2}}^-(z=z_{160}) = R_{\lambda_{s2}}^{160} \times I_{\lambda_{s2}}^+(z=z_{160});
\end{aligned}$$

[0061] The indices $^+$ and $-$ represent propagation in fiber **110** from left to right and from right to left, respectively. I_p , $I_{\lambda_{s1}}$, and $I_{\lambda_{s2}}$ represent the intensities of energy propagating in fiber **110** at wavelengths λ_p , λ_{s1} and λ_{s2} , respectively. α_p , α_1 and α_2 are the loss coefficients of energy propagating in fiber **110** at wavelengths λ_p , λ_{s1} and λ_{s2} , respectively, due to, for example, imperfections, scattering and/or splicing in fiber **110**. g_p , g_1 , \tilde{g}_1 and g_2 are the Raman gain coefficients, respectively, of energy propagating in fiber **110** at wavelengths λ_p , λ_{s1} and λ_{s2} , respectively, due to stimulated Raman scattering (SRS). It is to be noted that g_1 and \tilde{g}_1 represent gain coefficients for energy at λ_{s1} which can correspond to the same or different portion(s) of the Raman gain spectrum of the Raman active material in the gain medium of fiber **110**. g_1 corresponds to SRS energy transfer from λ_p to λ_{s1} and \tilde{g}_1 corresponds to SRS energy transfer from λ_{s1} to λ_{s2} , with respect to λ_{s1} . g_2 is the Raman gain coefficient for the transfer of energy from λ_{s1} to λ_{s2} , with respect to λ_{s2} , and is defined by $g_2 = (\lambda_{s2}/\lambda_{s1})(\tilde{g}_1)$. Additionally, in the boundary conditions, $R_{\lambda_{sy}}^x$ is the reflectance of reflector x at wavelength λ_{sy} , where reflectance is the ratio between reflected and incident intensity.

[0062] Based on these equations, it is believed that after reaching generation threshold the intensity of energy output by fiber **110** at wavelength λ_{s1} increases monotonically as the intensity of energy at wavelength λ_p input into fiber **110** is increased until the intensity of energy at λ_p reaches a value I_{crit} . Below I_{crit} , the intensity of energy output by fiber **110** at wavelength λ_{s2} is about zero. Above I_{crit} , the intensity of energy output by fiber **110** at wavelength λ_{s2} increases monotonically while the energy output by fiber **110** at wavelength λ_{s1} remains substantially constant. The particular value of I_{crit}

depends, at least in part, upon the transmission of reflectors 130 and 160.

[0063] Fig. 2 shows the calculated output intensities for fiber 110 for system 1000 as a function of the intensity of the pump energy (λ_p) where the reflectance of reflector 130 for energy impinging thereon at wavelength λ_{s1} is varied (20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%) and where reflector 160 reflects 50% of energy impinging thereon at wavelength λ_{s2} . In this example, λ_{s2} is 1480nm, λ_{s1} is 1455nm, and fiber 110 is formed of fused silica with GeO₂ as the Raman active material.

[0064] Fig. 3 shows a Raman fiber laser system 2000 in which fiber 110 includes reflector 125 and pairs of reflectors 120 and 130, and 150 and 160. Fiber 110 also includes a pair of reflectors 200 and 210. Reflector 200 is configured to reflect substantially all (e.g., about 100%) energy impinging thereon at a wavelength λ_{s3} , where $\lambda_{s3}^{-1} = \lambda_{s2}^{-1} - \lambda_{r3}^{-1}$, where (c/λ_{r3}) is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in the gain medium of fiber 110 (λ_{r3}^{-1} may be the same as or different from λ_{r2}^{-1} and/or λ_{r1}^{-1}). Reflector 210 is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength λ_{s3} . Reflectors 200 and 210 form a resonance cavity 220 in fiber 110 for energy at wavelength λ_{s3} .

[0065] With this arrangement, energy at wavelength λ_p generally propagates in fiber 110 as described above. In addition, energy at wavelengths λ_{s1} and λ_{s2} generally is formed and propagates in fiber 110 as described above. As energy at wavelength λ_{s2} propagates through fiber 110 (e.g., in the overlapping region of cavities 170 and 220), it interacts with the Raman active material in the gain medium of fiber 110 to create energy at wavelength λ_{s3} . Energy at wavelength λ_{s3} in cavity 220 that is propagating in the reverse direction is reflected by reflector 200 and then propagates through fiber 110 in the forward direction. Energy at wavelength λ_{s3} propagating in cavity 220 in the forward

direction impinges on reflector 210. Some of the energy at λ_{s3} impinging on reflector 210 is reflected by reflector 210 and then propagates through cavity 220 in the reverse direction, and some of the energy at λ_{s3} impinging on reflector 210 passes through reflector 210 and exits fiber 110 (e.g., at end 115). It is to be noted that, in this embodiment, λ_p directly pumps only λ_{s1} , λ_{s2} is directly pumped by only λ_{s1} , and that λ_{s3} is directly pumped only by λ_{s2} .

[0066] Resonance cavities 140 and 170 are linked resonance cavities, and resonance cavities 170 and 220 are linked resonance cavities.

[0067] Fig. 4 shows a Raman fiber laser system 3000 in which fiber 110 includes reflector 125 and pairs of reflectors 120 and 130, 150 and 160, and 200 and 210. Fiber 110 also includes a pair of reflectors 300 and 310. Reflector 300 is configured to reflect substantially all (e.g., about 100%) energy impinging thereon at a wavelength λ_{s4} , where $\lambda_{s4}^{-1} = \lambda_{s3}^{-1} - \lambda_{r4}^{-1}$, where (c/λ_{r4}) is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in the gain medium of fiber 110 (λ_{r4}^{-1} may be the same as or different from λ_{r3}^{-1} , λ_{r2}^{-1} and/or λ_{r1}^{-1}). Reflector 310 is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength λ_{s4} . Reflectors 300 and 310 form a resonance cavity 320 in fiber 110 for energy at wavelength λ_{s4} .

[0068] With this arrangement, energy at wavelength λ_p generally propagates in fiber 110 as described above. In addition, energy at wavelengths λ_{s1} , λ_{s2} and λ_{s3} generally is formed and propagates in fiber 110 as described above. As energy at wavelength λ_{s3} propagates through fiber 110 (e.g., in the overlapping region of cavities 220 and 320), it interacts with the Raman active material in the gain medium of fiber 110 to create energy at wavelength λ_{s4} . Energy at wavelength λ_{s4} in cavity 320 that is propagating in the reverse direction is reflected by reflector 300 and then propagates

through fiber 110 in the forward direction. Energy at wavelength λ_{s4} propagating in cavity 320 in the forward direction impinges on reflector 310. Some of the energy at λ_{s4} impinging on reflector 310 is reflected by reflector 310 and then propagates through cavity 320 in the reverse direction, and some of the energy at λ_{s4} impinging on reflector 310 passes through reflector 310 and exits fiber 110 (e.g., at end 115). It is to be noted that, in this embodiment, λ_p directly pumps only λ_{s1} , λ_{s2} is directly pumped by only λ_{s1} , λ_{s3} is directly pumped only by λ_{s2} , and λ_{s4} is directly pumped only by λ_{s3} .

[0069] Resonance cavities 140 and 170 are linked cavities, resonance cavities 170 and 220 are linked cavities, and resonance cavities 170 and 220 are linked cavities.

[0070] While the foregoing description has been made for a system containing two, three or four pairs of reflectors, the invention is not limited in this manner. Rather, the number of pairs of reflectors can be greater than two (e.g., five pairs of reflectors, six pairs of reflectors, seven pairs of reflectors, eight pairs of reflectors, nine pairs of reflectors, 10 pairs of reflectors, etc.). In general, the pairs of reflectors are arranged so that each pair of reflectors forms a resonance cavity at a respective wavelength corresponding to a Raman Stokes shift. Typically, each pair of reflectors includes one reflector that reflects substantially all (e.g., about 100%) energy at the Raman Stokes shift wavelength (e.g., disposed closer to the point of the optical fiber where the pump energy enters the fiber) and one reflector that partially reflects energy at the Raman Stokes shift wavelength (e.g., disposed further from the point of the optical fiber where the pump energy enters the fiber). Usually, the resonance cavities are arranged so that the resonance cavity for energy at the wavelength λ_{sn} overlaps only with a maximum of two resonance cavities. One of the two resonance cavities is for energy at the wavelength λ_{sn-1} , where $\lambda_{sn-1}^{-1} = \lambda_{sn}^{-1} + \lambda_m^{-1}$ and the other of the two resonance cavities is for energy at the wavelength λ_{sn+1} , where $\lambda_{sn+1}^{-1} = \lambda_{sn}^{-1} + \lambda_{m+1}^{-1}$ (λ_m^{-1} and λ_{m+1}^{-1} being Stokes shifts within the Raman gain spectrum of the active material in the gain medium of fiber 110; λ_m^{-1} and λ_{m+1}^{-1} being the same or different). Generally, relative to the resonance cavity for energy at wavelength λ_{sn} , the resonance cavity for energy at λ_{sn-1} is closer to the

portion of fiber 110 where the energy at wavelength λ_p enters fiber 110, and the resonance cavity for energy at λ_{sn+1} is further from the portion of fiber 110 where the energy at wavelength λ_p enters fiber 110. Typically, the resonance cavity having a resonance frequency closest to λ_p^{-1} overlaps with only one other resonance cavity, and the resonance cavity having a resonance frequency furthest from λ_p^{-1} overlaps with only one other resonance cavity.

[0071] Although systems have been described in which each resonance cavity is formed of a pair of reflectors with one reflector that only partially reflects energy at the corresponding wavelength of the resonance cavity, the invention is not limited in this sense. In certain embodiments, one or more of the pairs of reflectors can have both reflectors that only partially reflect energy at the corresponding wavelength of the resonance cavity. In some embodiments, one or more of the pairs of reflectors can have both reflectors that reflect substantially (e.g., about 100%) the energy at the corresponding wavelength of the resonance cavity.

[0072] Moreover, the invention is not limited to systems in which the reflectance of a reflector is fixed. In some embodiments, the reflectance of a reflector can be variable. For example, the amount of energy reflected off reflectors 130, 160, 210, and/or 310 at their respective corresponding wavelengths can be variable. In certain embodiments, the amount of energy reflected off reflectors 120, 150, 200, and/or 300 at their respective corresponding wavelengths can be variable. Various combinations of tunable reflectors are contemplated. Furthermore, these systems can include, for example, appropriate electronics to form a feedback loop so that the systems can monitor the intensity of energy output at one or more wavelengths and vary the reflectance of one or more reflectors (e.g., vary the reflectance of one or more reflectors in real time) to obtain one or more desired output intensities at one or more wavelengths.

[0073] In certain embodiments, a reflector can be formed of a variable output coupler. Such couplers are described, for example, in commonly owned P.C.T. Patent Application Serial PCT/US02/19420, filed on June 19, 2002, and entitled "Apparatus and

Method for Variable Optical Output Control”, and published as WO 03/001262 A1 on January 3, 2003, and which is hereby incorporated by reference.

[0074] In addition, one or more of the resonance cavities contained within a Raman fiber laser system can contain a suppressor that is designed to substantially reduce (e.g., substantially eliminate) the formation of unwanted energy in the resonance cavity or cavities. Typically, such unwanted energy corresponds to energy at higher order Stokes shifts than the resonance energy for the resonance cavity. The suppressor can be, for example, a long period grating having a resonance frequency corresponding to the frequency of the undesired energy.

[0075] In some embodiments, an optical fiber can be formed of more than one segment of fiber coupled together. For example, Fig. 5 shows a Raman fiber laser system 7000 including laser 100 and an optical fiber 705. Optical fiber 705 has a first section 720 with a gain medium containing a Raman active material and a second section 730 with a gain medium containing a Raman active material. Sections 720 and 730 are coupled together at point 710 (e.g., spliced together). The Raman active material of the gain medium in section 720 may be the same as or different from the Raman active material of the gain medium in section 730. In some embodiments, sections 720 and 730 may have the same Raman active material in their respective gain media, but the concentration of the Raman active material in section 720 is different than the concentration of the Raman active material in section 730. In certain embodiments, sections 720 and 730 may have the same Raman active material in their respective gain media, but the radius of the portion of section 720 that contains the Raman active material is different than the radius of the portion of section 730 that contains the Raman active material in section 730. Various combinations of active material, radius and active material concentration in segments 720 and 730, respectively, can be used. It is to be noted that in embodiments where sections 720 and 730 contain the same Raman active material having the same concentration and radius, the position of splice point 710 can have substantially no impact on the performance of system 7000.

[0076] Optical fiber 705 includes reflector 125, and pairs of reflectors 725 and 735 forming resonance cavity 740. Reflector 725 is configured to reflect substantially all (e.g., about 100%) energy impinging thereon at wavelength λ_{s1} , where $\lambda_{s1}^{-1} = \lambda_p^{-1} - \lambda_{r1}^{-1}$ and (c/λ_{r1}) is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in section 720. Reflector 735 is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength λ_{s1} . Reflectors 725 and 735 form a resonance cavity 740 in fiber 705 for energy at wavelength λ_{s1} . A portion of resonance cavity 740 is in section 720 of fiber 705, and a portion of resonance cavity 740 is in section 730 of fiber 705.

[0077] Fiber 705 further includes a pair of reflectors 750 and 760. Reflector 750 is configured to reflect substantially all (e.g., about 100%) energy impinging thereon at wavelength $\lambda_{s1'}$, where $\lambda_{s1'}^{-1} = \lambda_{s1}^{-1} - \lambda_{r1}^{-1}$ and (c/λ_{r1}) is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in section 730. Reflector 760 is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength $\lambda_{s1'}$. Reflectors 750 and 760 form a resonance cavity 770 in fiber 705 for energy at wavelength $\lambda_{s1'}$.

[0078] With this arrangement, energy at wavelength λ_p enters optical fiber 705 in section 720. The energy at λ_p propagates through section 720 of fiber 705 and impinges upon reflector 125 where it is reflected and propagates in section 720 of fiber 705 in the reverse direction. As energy at λ_p propagates through section 720 of fiber 705 it interacts with the Raman active material in the gain medium of section 720 of fiber 705 to create energy at wavelength λ_{s1} . Energy at λ_{s1} in cavity 740 that is propagating in the forward direction can propagate in the gain medium of sections 720 and 730 prior to impinging upon reflector 735. A portion of the energy at λ_{s1} that impinges on reflector 735

continues to propagate to propagate through fiber **705** in the forward direction and exits fiber **705** (e.g., at an end **715** of fiber **705**). The portion of energy at λ_{s1} that is reflected by reflector **735** can propagate in sections **720** and **730** of fiber **705** in the reverse direction until it reaches reflector **725** where it is reflected and propagates through fiber **705** in the forward direction within cavity **740**.

[0079] As energy at λ_{s1} propagates in section **730** of fiber **705** (e.g., between splice point **710** and reflector **735**), it can interact with the Raman active material of the gain medium of section **730** to create energy at wavelength $\lambda_{s1'}$. Energy at wavelength $\lambda_{s1'}$ in cavity **770** that is propagating in the reverse direction is reflected by reflector **750** and then propagates through fiber **705** in the forward direction. Energy at wavelength $\lambda_{s1'}$ propagating in cavity **770** in the forward direction impinges on reflector **760**. Some of the energy impinging on reflector **760** is reflected by reflector **760** and then propagates through cavity **770** in the reverse direction, and some energy at $\lambda_{s1'}$ impinging on reflector **760** passes through reflector **760** and exits fiber **705** (e.g., at end **715**). It is to be noted that, in this embodiment, λ_p directly pumps only λ_{s1} , and that $\lambda_{s1'}$ is directly pumped only by λ_{s1} . The order of the reflectors, however, can be varied. For example, reflector **760** can be located to the left of reflector **735**, or the right side of splice point **710**, or the like.

[0080] Resonance cavities **740** and **770** are linked cavities.

[0081] Without wishing to be bound by theory, it is believed that this design can allow for enhanced control of the intensity of energy output by fiber **705** at wavelengths λ_{s1} and $\lambda_{s1'}$ by controlling (e.g., independently controlling) the transmission of reflectors **735** and/or **760**, and/or the intensity of the pump energy. It is believed that the performance of fiber **705**, in the case where reflector **735** is positioned in close proximity to reflector **760** (i.e., $z_{125} \approx z_{750} \approx z_{710}$ and $z_{735} \approx z_{760}$), can be explained, at least in part, using the following system of equations.

$$\frac{dI_p^+}{dz} = -g_p(I_{\lambda_{s1}}^+ + I_{\lambda_{s1}}^-) \times I_p^+ - \alpha_p I_p^+ = -\frac{dI_p^-}{dz}$$

$$\frac{d\hat{I}_{\lambda_{s1}}^+}{dz} = g_1 \hat{I}_{\lambda_{s1}}^+ \times (I_p^+ + I_p^-) - \alpha_1 \hat{I}_{\lambda_{s1}}^+ = -\frac{d\hat{I}_{\lambda_{s1}}^-}{dz}$$

$$\frac{d\tilde{I}_{\lambda_{s1}}^+}{dz} = -\tilde{g}_1 \tilde{I}_{\lambda_{s1}}^+ \times (I_{\lambda_{s1'}}^+ + I_{\lambda_{s1'}}^-) - \tilde{\alpha}_1 I_{\lambda_{s1}}^+ = -\frac{d\tilde{I}_{\lambda_{s1}}^-}{dz}$$

$$\frac{dI_{\lambda_{s1'}}^+}{dz} = g_{1'} I_{\lambda_{s1'}}^+ \times (\tilde{I}_{\lambda_{s1}}^+ + \tilde{I}_{\lambda_{s1}}^-) - \alpha_{1'} I_{\lambda_{s1'}}^+ = -\frac{dI_{\lambda_{s1'}}^-}{dz}$$

[0082] The indices $^+$ and $-$ represent propagation in fiber **705** from left to right and from right to left, respectively. I_p , $I_{\lambda_{s1}}$, and $I_{\lambda_{s1'}}$ represent the intensities of energy propagating in fiber **705** at wavelengths λ_p , λ_{s1} and $\lambda_{s1'}$, respectively. α_p , $\alpha_{1'}$ are the loss coefficients of energy propagating in fiber **705** at wavelengths λ_p and $\lambda_{s1'}$, respectively, due to, for example, imperfections, scattering and/or splicing in fiber **705**. α_1 and $\tilde{\alpha}_1$ are loss coefficients for sections **720** and **730**, respectively, for energy at wavelength λ_{s1} (e.g., due to imperfections, scattering and/or splicing). g_p and $g_{1'}$ are the Raman gain coefficients for energy propagating in fiber **705** at wavelengths λ_p and $\lambda_{s1'}$, respectively, due to power gain from stimulated Raman scattering (SRS). g_1 , \tilde{g}_1 are Raman gain coefficients for energy propagating in sections **720** and **730**, respectively, at λ_{s1} due to power gain from stimulated Raman scattering (SRS). $g_{1'} = (\lambda_{s1'}/\lambda_{s1})(\tilde{g}_1)$.

The boundary conditions at the reflectors and splice point are given by:

$$I_p^+(z=0) = I_0; I_p^-(z=z_{125}) = R_{\lambda_p}^{125} \times I_p^+(z=z_{125});$$

$$\hat{I}_{\lambda_{s1}}^+(z=z_s) = \tilde{I}_{\lambda_{s1}}^+(z=z_s); \hat{I}_{\lambda_{s1}}^-(z=z_s) = \tilde{I}_{\lambda_{s1}}^-(z=z_s);$$

$$\hat{I}_{\lambda_{s1}}^+(z=z_{725}) = R_{\lambda_{s1}}^{725} \times \hat{I}_{\lambda_{s1}}^-(z=z_{725}); \tilde{I}_{\lambda_{s1}}^-(z=z_{735}) = R_{\lambda_{s1}}^{735} \times \tilde{I}_{\lambda_{s1}}^+(z=z_{735});$$

$$I_{\lambda_{s1'}}^+(z=z_{750}) = R_{\lambda_{s1'}}^{750} \times I_{\lambda_{s1'}}^-(z=z_{750}); I_{\lambda_{s1'}}^-(z=z_{760}) = R_{\lambda_{s1'}}^{760} \times I_{\lambda_{s1'}}^+(z=z_{760});$$

Here z_s is the splice point of two fibers, and z_x and $R_{\lambda_{s1}}^x$ are as defined above. I_0 is the total pump power.

[0083] Fig. 6 shows a Raman fiber laser system 8000 including laser 100 and optical fiber 705 with sections 720 and 730 coupled at point 710. Fiber 705 includes reflector 125, and pairs of reflectors 725 and 735, and 750 and 760, forming resonance cavities 740 and 770, respectively. Fiber 110 also includes a pair of reflectors 850 and 860 (e.g., fiber Bragg gratings). Reflector 850 is configured to reflect substantially all (e.g., about 100%) energy impinging thereon at wavelength $\lambda_{s2'}$, where $\lambda_{s2'}^{-1} = \lambda_{s1'}^{-1} - \lambda_{r2'}^{-1}$, and $(c/\lambda_{r2'})$ is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in section 730 ($\lambda_{r2'}^{-1}$ can be the same as or different from $\lambda_{r1'}^{-1}$). Reflector 860 is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength $\lambda_{s2'}$. Reflectors 850 and 860 form a resonance cavity 870 in fiber 705 for energy at wavelength $\lambda_{s2'}$.

[0084] With this arrangement, energy at λ_p generally propagates in fiber 705 as described above. In addition energy at wavelengths λ_{s1} and $\lambda_{s1'}$ generally is formed and propagates through fiber 705 as described above. As energy at wavelength $\lambda_{s1'}$ propagates through section 730 of fiber 705 (e.g., in the region overlapping cavities 770 and 870), it interacts with the Raman active material of section 730 of fiber 705 to create energy at wavelength $\lambda_{s2'}$. Energy at wavelength $\lambda_{s2'}$ in cavity 870 that is propagating in the reverse direction is reflected by reflector 850 and then it propagates through fiber 705 in the forward direction. Energy at wavelength $\lambda_{s2'}$ propagating in cavity 870 in the forward direction impinges on reflector 860. Some of the energy at $\lambda_{s2'}$ impinging on reflector 860 is reflected by reflector 860 and then propagates through cavity 870 in the reverse direction, and some of the energy at $\lambda_{s2'}$ impinging on reflector 860 passes through reflector 860 and exits fiber 705 (e.g., at end 715). It is to be noted that, in this embodiment, λ_p directly pumps only λ_{s1} , $\lambda_{s1'}$ is directly pumped only by λ_{s1} , and $\lambda_{s2'}$ is directly pumped only by $\lambda_{s1'}$.

[0085] Resonance cavities 740 and 770 are linked cavities, and resonance cavities

770 and **870** are linked cavities.

[0086] Fig. 7 shows a Raman fiber laser system **9000** including laser **100** and optical fiber **705** with sections **720** and **730** coupled at point **710**. Fiber **705** includes reflector **125**, and pairs of reflectors **725** and **735**, **750** and **760**, and **850** and **860**, forming resonance cavities **740**, **770** and **870**, respectively. Fiber **705** also includes a pair of reflectors **950** and **960** (e.g., fiber Bragg gratings). Reflector **950** is configured to reflect substantially all (e.g., about 100%) energy impinging thereon at wavelength λ_{s3} , where $\lambda_{s3}^{-1} = \lambda_{s2}^{-1} - \lambda_{r3}^{-1}$, and (c/λ_{r3}) is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in section **730** (λ_{s3}^{-1} can be the same as or different than λ_{r1}^{-1} and/or λ_{r2}^{-1}). Reflector **960** is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength λ_{s3} . Reflectors **950** and **960** form a resonance cavity **970** in fiber **705** for energy at wavelength λ_{s3} .

[0087] With this arrangement, energy at λ_p generally propagates in fiber **705** as described above. In addition energy at wavelengths λ_{s1} , λ_{s1}' and λ_{s2} , generally is formed and propagates through fiber **705** as described above. As energy at wavelength λ_{s2} , propagates through section **730** of fiber **705** (e.g., in the region overlapping cavities **870** and **970**), it interacts with the Raman active material of section **730** of fiber **705** to create energy at wavelength λ_{s3} . Energy at wavelength λ_{s3} in cavity **970** that is propagating in the reverse direction is reflected by reflector **950** and then it propagates through fiber **705** in the forward direction. Energy at wavelength λ_{s3} propagating in cavity **970** in the forward direction impinges on reflector **960**. Some of the energy at λ_{s3} impinging on reflector **960** is reflected by reflector **960** and then propagates through cavity **970** in the reverse direction, and some of the energy at λ_{s3} impinging on reflector **960** passes through reflector **960** and exits fiber **705** (e.g., at end **715**). It is to be noted that, in this embodiment, λ_p directly pumps only λ_{s1} , λ_{s1}' is directly pumped only by λ_{s1} , λ_{s2} is

directly pumped only by $\lambda_{s1'}$, and $\lambda_{s3'}$ is directly pumped only by $\lambda_{s2'}$.

[0088] Resonance cavities 740 and 770 are linked cavities, resonance cavities 770 and 870 are linked cavities, and resonance cavities 870 and 970 are linked cavities.

[0089] Although optical fibers with coupled segments having certain arrangements of splice points and reflectors have been described, the invention is not limited to such arrangements. In general, the splice points and reflectors can be arranged as appropriate to achieve one or more desired output intensities at one or more output wavelengths. As an example, with reference to Fig. 7, splice point 710 can optionally be between reflectors 725 and 750 or between reflectors 735 and 760. As another example, with reference to Fig. 8, splice point 710 can optionally be between reflectors 725 and 750, between reflectors 735 and 850, between reflectors 850 and 760 or between reflectors 760 and 860. In a further example, with reference to Fig. 9, splice point 710 can optionally be between reflectors 725 and 750, between reflectors 735 and 850, between reflectors 850 and 760, between reflectors 760 and 950, between reflectors 950 and 860 or between reflectors 960 and 860. Typically, the reflectors are arranged so that the resonance cavity for energy at a particular wavelength λ_{sn} overlaps only with two resonance cavities (see discussion above). Moreover, it is to be understood that the number of resonance cavities, or portions of resonance cavities, in a particular segment of fiber can be varied as desired.

[0090] In addition, while systems containing an optical fiber with two segments of material have been disclosed, optical fibers having different numbers of segments can also be used. In general, the optical fiber can have N segments, where N is an integer greater than or equal to one. For example, the optical fiber can include more than two segments of material having the same or different Raman active material(s) (e.g., three segments, four segments, five segments, six segments, seven segments, eight segments, nine segments, 10 segments, etc.). In general, each section of the optical fiber can have a gain medium with an Raman active material which can be the same or different than the Raman active material in the gain medium of the neighboring section(s) of the fiber. In

some embodiments, all sections of the optical fiber have a gain medium with the same Raman active material. In certain embodiments, all sections of the optical fiber have a gain medium with a different Raman active material than the Raman active material in the gain medium of the other sections. In some embodiments the Raman active material in the gain medium of the other sections can alternate. For example, a three-section optical fiber can be formed in which the Raman active material of the gain medium of the first and third sections is the same, and in which the Raman active material in the gain medium in the middle section is different. Other arrangements are contemplated.

[0091] Furthermore, while Raman fiber lasers and Raman fiber laser systems have been described in which sections of the optical fiber are spliced together, the invention is not limited in this sense. Generally, the sections of the fiber are coupled together so that energy can propagate therebetween. Typically, the sections of fiber are contiguous. For example, in some embodiments, two neighboring sections of the optical fiber can be connected by a lens (e.g., a Green lens). Optionally, free-space optics can be used to couple one or more segments of fiber.

[0092] Fig. 8 is a schematic view of an embodiment of a fiber amplifier system **11000** in which a Raman fiber laser system **1105** that outputs energy at four wavelengths ($\lambda_1, \lambda_2, \lambda_3, \lambda_4$) is used to amplify the signals propagating along fibers **1122**, **1124**, **1126**, and **1128** respectively. These output wavelengths exit system **1105** and enter a fiber **1108**. Fiber **1108** is coupled to a splitter **1110**, which couples a portion of the output energy at each wavelength ($\lambda_1, \lambda_2, \lambda_3, \lambda_4$) into fibers **1112**, **1114**, **1116**, and **1118**. The pump energy at each wavelength in each fiber **1112**, **1114**, **1116**, and **1118** is coupled into fibers **1122**, **1124**, **1126**, and **1128** respectively, via couplers **1132**, **1134**, **1136**, and **1138** respectively. At least a portion of each of fibers **1122**, **1124**, **1126**, and **1128** contain a gain medium that has a Raman active material. In fibers **1122**, **1124**, **1126**, and **1128** the input signals interact with the pump energy from fibers **1112**, **1114**, **1116**, and **1118**, respectively and are amplified by stimulated Raman scattering.

[0093] Of course such a system is not limited to amplification of signals in four

fibers, or amplification by four wavelengths. In general, a Raman fiber laser system with N output wavelengths, where N is an integer greater than or equal to one (e.g., one, two, three, four, five, six, seven, eight, nine, 10, etc.) can be used to amplify the signal in M different fibers, where M is an integer greater than or equal to one (e.g., one, two, three, four, five, six, seven, eight, nine, 10, etc.). In certain embodiments, M can be, for example, on the order of one hundred or more. In some embodiments, all the fibers in which the signals are amplified by the Raman fiber laser may be bound together in a single or several cables running in parallel (e.g., an under water fiber optic and/or ultra long haul applications).

[0094] Figure 9 depicts an embodiment of a fiber amplifier system **12000**. System **12000** utilizes four Raman fiber laser systems **1210**, **1220**, **1230**, and **1240**, each system emitting energy at an output wavelength that exits systems **1210**, **1220**, **1230**, and **1240** through fibers **1250**, **1260**, **1270**, and **1280**, respectively. The output energy from each laser **1210**, **1220**, **1230**, and **1240**, is coupled into at least one of the fibers **1112**, **1114**, **1116**, and **1118** via a cross-coupler (e.g., a WDM) **1290**. In some embodiments, a portion of output energy at each wavelength generated by each laser system **1210**, **1220**, **1230**, and **1240** is coupled into each fiber **1112**, **1114**, **1116**, and **1118**, respectively via coupler **1290**. The pump energy at each wavelength in each fiber **1112**, **1114**, **1116**, and **1118** is coupled into fibers **1122**, **1124**, **1126**, and **1128** respectively, via coupler **1132**, **1134**, **1136**, and **1138** respectively. At least a portion of fibers **1122**, **1124**, **1126**, and **1128** contain a gain medium that has a Raman active material. In fibers **1122**, **1124**, **1126**, and **1128** the input signals interact with the pump energy and are amplified by stimulated Raman scattering.

[0095] Such a system **12000** is not limited to four lasers or four fibers. Any number of lasers may amplify the signal in any number of fibers. Moreover, a given fiber laser system can output more than one wavelength, which can be coupled into one or more fibers.

[0096] A further example of a fiber laser system **13000** is depicted schematically

in Figure 10. System **13000** includes a pump laser **1310** (e.g., a semiconductor diode laser) that is connected to a coupler **1350** via fibers **1320**, **1330** and **1340**. Combiner **1350** is connected to a fiber laser **1370** (e.g., a Ytterbium-doped double clad fiber) via a coupler **1360**. Laser **1370** is in turn connected to Raman a fiber laser **1390** (e.g., a Raman fiber laser having the structure described herein) via a coupler **1380**, and a laser **1390** is connected to an output cascade **1510** via fiber a coupler **1400**. In certain embodiments, laser **1390** and output cascade **1510** are integrated in a single unit.

[0097] During operation, energy at wavelength Λ_p is generated by pump laser **1310** and propagates along fibers **1320**, **1330**, and **1340** and is coupled into fiber laser **1370** via combiner **1350** and coupler **1360**. The energy at Λ_p is converted by laser **1370** into energy at λ_p . Energy at λ_p exits laser **1370**, propagates along coupler **1380** and is coupled into Raman fiber laser **1390**. Energy at wavelength λ_p is converted to energy at one or more longer wavelengths. The energy at these wavelengths is coupled into output cascade **1510** by fiber **1400**. Cascade **1510** optionally includes variable output couplers that can be dynamically adjusted to regulate the amount of energy allowed to exit system **13000** at desired wavelengths.

[0098] While certain embodiments have been described, the invention is not limited to these embodiments. For example, one or more sections of an optical fiber can be substantially devoid of a gain medium having a Raman active material. As a further example, the reflectors need not be in the form of fiber Bragg gratings. For example, one or more of the reflectors can be a loop mirror, or one or more reflectors can be in the form of a coated mirror (e.g., a coated mirror at one or both ends of a section of optical fiber). As another example, the suppressor(s) need not be in the form of LPG(s). For example, one or more of the suppressors can be in the form of gratings e.g., short period gratings, slanted gratings, etc.) that are substantially non-perpendicular to the length of the fiber along which energy propagates. In these embodiments, the angle and/or period of the gratings can be selected to scatter one or more wavelengths of interest (e.g., one or more higher order Raman Stokes shift wavelengths). As an additional example, the type of laser used for pumping can be varied. Examples of lasers that can be used include

semiconductor diode lasers (e.g., high power semiconductor diode lasers), double clad doped fiber lasers, conventional free space coupled lasers, and the like. As another example, various types of optical fibers can be used, including, for example, double clad optical fibers and polarization maintaining optical fibers. Furthermore, the optical fibers can be formed of, for example, silica based materials (e.g., fused silica based) or fluoride-based materials. As yet another example, the relative and/or absolute lengths of one or more of the sections of the optical fiber can be varied based upon the intended use of the Raman fiber laser.

[0099] Moreover, while the fibers and systems have been described as Raman fiber lasers and Raman fiber laser systems, those skilled in the art will appreciate that the general concepts described can be extended to provide amplifiers and amplifier systems. Generally, a fiber amplifier provides gain for energy at a wavelength or wavelength range of interest without the use of a resonance cavity (e.g., without a resonator) or with an optical cavity operating below resonance threshold. Fig. 11 is a schematic view of an embodiment of a fiber amplifier system **10000** in which a fiber **1050** is used as a signal amplifier. Fiber **1050** can be formed of multiple segments of fiber or a single segment of fiber. To operate at below resonance threshold, for example, one or more of the reflectors can be removed from fiber **1050** and/or the reflectivity of one or more of the reflectors can be reduced. An input signal enters system **10000** via fiber **1005** (the reflectors can be, for example, otherwise arranged as described above). Energy source **1060** emits a pump signal **1070**. The input signal in fiber **1005** and pump signal **1070** are coupled into fiber **1050** via coupler **1080**. Such couplers are known to those skilled in the art. Pump signal **1070** interacts with the Raman active material(s) in the sections of fiber **1050**, and the input signal is amplified. A device **1090** (e.g., a WDM coupler) separates the amplified input signal from the Stokes shifted pump signal so that the Stokes shifted pump signal travels along fiber **1015**, and the amplified input signal travels along fiber **1025**. While Fig. 13 shows one embodiment of fiber **1050** in a fiber amplifier system, other fiber amplifier systems in which fiber **1050** can be used will be apparent to those of skill in the art.

[0100] Furthermore, while the foregoing discussion has been with respect to linked resonance cavities, the invention is not so limited. In certain embodiments, the systems can be formed of a hybrid of linked and nested resonance cavities. Nested resonance cavities refer to resonance cavities in which one resonance cavity is entirely contained within another resonance cavity. For example, Fig. 12 shows a system **12000** including an optical fiber **110**, a pair of reflectors **12010** and **12020** (which reflect substantially all energy at wavelength λ_{s1}) a pair of reflectors **12030** and **12040** (which reflect substantially all energy at wavelength λ_{s2}) a pair of reflectors **12050** and **12060** (which reflect substantially all energy at wavelength λ_{s3}) a pair of reflectors **12070** and **12080** (which reflect substantially all energy at wavelength λ_{s4}) and a pair of reflectors **12090** and **12100** (which reflect substantially all energy at wavelength λ_{s5}) where λ_{sn} is determined as described above. With this configuration, reflectors **12030** and **12040** form a resonance cavity **12110** that is nested within a resonance cavity **12120** formed by reflectors **12010** and **12020**, and reflectors **12070** and **12080** form a resonance cavity **12140** that is nested within a resonance cavity **12130** formed by reflectors **12090** and **12100**. In addition, reflectors **12050** and **12060** form a resonance cavity **12150**. Resonance cavity **12150** is linked with resonance cavity **12110**, and resonance cavity **12150** is linked with resonance cavity **12120**. Resonance cavity **12150** is linked with resonance cavity **12130**, and resonance cavity **12150** is linked with resonance cavity **12140**.

Other embodiments are in the claims.

WHAT IS CLAIMED IS: